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Far-Field Deposition from Space Shuttle Launches at John F. Kennedy Space Center, Florida

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ABSTRACT

Far-field deposition outside of the near-field plume zone occurs from Space Shuttle launches as a result of movement of the launch cloud with prevailing meterological conditions. Paths taken by the launch cloud are highly variable due to varying wind direction and speed. Direction and amount of deposition are predicted by the Rocket Exhaust Effluent Diffusion Model (REEDM). Five launches have been sampled to quantify far-field deposition. Drop counts were made for STS-51-A (8 November 1984) but were not sufficient to quantify deposition. Drop counts together with drop size measurements were made for STS-51-F (29 July 1985) and estimates of deposition derived. For two launches, STS-51-D (12 April 1985) and STS-51-B (29 April 1985) leaf samples in the deposition path were collected and washed to recover deposition. Leaf samples and drop counts were made for STS-61-B (26 November 1985). Measurements of chloride deposition by these techniques ranged from 25 mg/m^2 to 5300 mg/m^2. Aluminum deposition from leaf samples ranged between 0.3 and 107.7 mg/m^2 and was generally between 1% to 10% of chloride deposition. The expected aluminum to chloride ratio in the ground cloud is 86.7%. Reasons for this difference are not known. Estimates of deposition from drop counts and from leaf samples were similar. Measured chloride deposition within the plume zone exceeded REEDM program predictions. Outside the plume zone but within about 1 km of the launch pad, measured deposition generally agreed with model predictions. Farther from the pad, deposition was equal or less than predicted. Degree of vegetation damage was related to amount of chloride deposition. Serious vegetation damage to many species occurred where chloride deposition values were greater than 1000 mg/m^2; sensitive species were damaged at levels of chloride deposition of 100 mg/m^2 or less.

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ACKNOWLEDGEMENTS

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INTRODUCTION

Launches of the Space Shuttle from John F. Kennedy Space Center produce environmental impacts resulting from the formation of an exhaust cloud (Bowie 1981, Knott et al. 1983). Major constituents of the exhaust cloud are carbon dioxide (CO_2), water (H_2O), aluminum oxide (Al_2O_3), and hydrogen chloride (HCl) (NASA 1979). The formation of the exhaust cloud occurs as a result of the combined effects of the ignition of the Solid Rocket Motors (SRM) and the Space Shuttle Main Engines (SSME) and the simultaneous dumping of several thousand kiloliters of sound suppression and cooling water onto the launch pad. In the turbulence of the rocket exhausts, atomization of the deluge water occurs; water droplets coagulate with aluminum oxide particulates and rapidly scavenge hydrogen chloride gas producing acidic deposition (Anderson and Keller 1983).

Typically, this exhaust cloud, termed the ground cloud, is directed horizontally northward by the structure of the flame trench but then rises as the horizontal velocity decreases (Knott et al. 1983). As the cloud rises it entrains ambient air eventually reaching a stabilization height (Bjorklund et al. 1982). The ground cloud is then carried by prevailing winds.

Near-field acute effects are produced by the ground cloud sweeping turbulently across the ground, vegetation, and lagoonal waters. Generally near-field effects occur within 0.5 km of the launch pad although they have extended up to 1.0 km away (Knott et al. 1983). Since the pH of droplets in this cloud can be <0.5 (Anderson and Keller 1983), near-field effects can be severe and include acute vegetation damage (Bowie 1981, Knott et al. 1983, Schmalzer et al. 1985) and fish kills (Knott et al. 1983, Milligan and Hubbard 1983, Hawkins et al. 1984).

Far-field effects are produced after the ground cloud stabilizes and moves with the prevailing winds. Deposition from this cloud causes spotting on vegetation and structures; this spotting may include acid burns from "wet" deposition or may be only dry residue, primarily Al_2O_3 (Knott et al. 1983, Anderson and Keller 1983). Deposition has been detected up to 22 km from the launch site.

Near-field deposition has been quantified for three launches, STS-11 (41-B), STS-13 (41-C) and STS-14 (41-D) (Dreschel and Hinkle 1984, Dreschel, Hall, and Hinkle 1985, Dreschel et al. 1985). In a typical launch such as STS-11 (41-B), approximately 3000 kg of chlorides and 7000 kg of particulates are deposited in the 22 ha near-field environment. Isopleths of this deposition indicate 100 g/m^2 or more of chlorides (Figure 1) and 200 g/m^2 or more of particulates (Figure 2) can be deposited in the near-field environment (Dreschel, Hall, and Hinkle 1985). This pattern occurs under conditions of light surface winds. With

CHLORIDE DEPOSITION: LAUNCH OF STS-11

(grams/square meter)

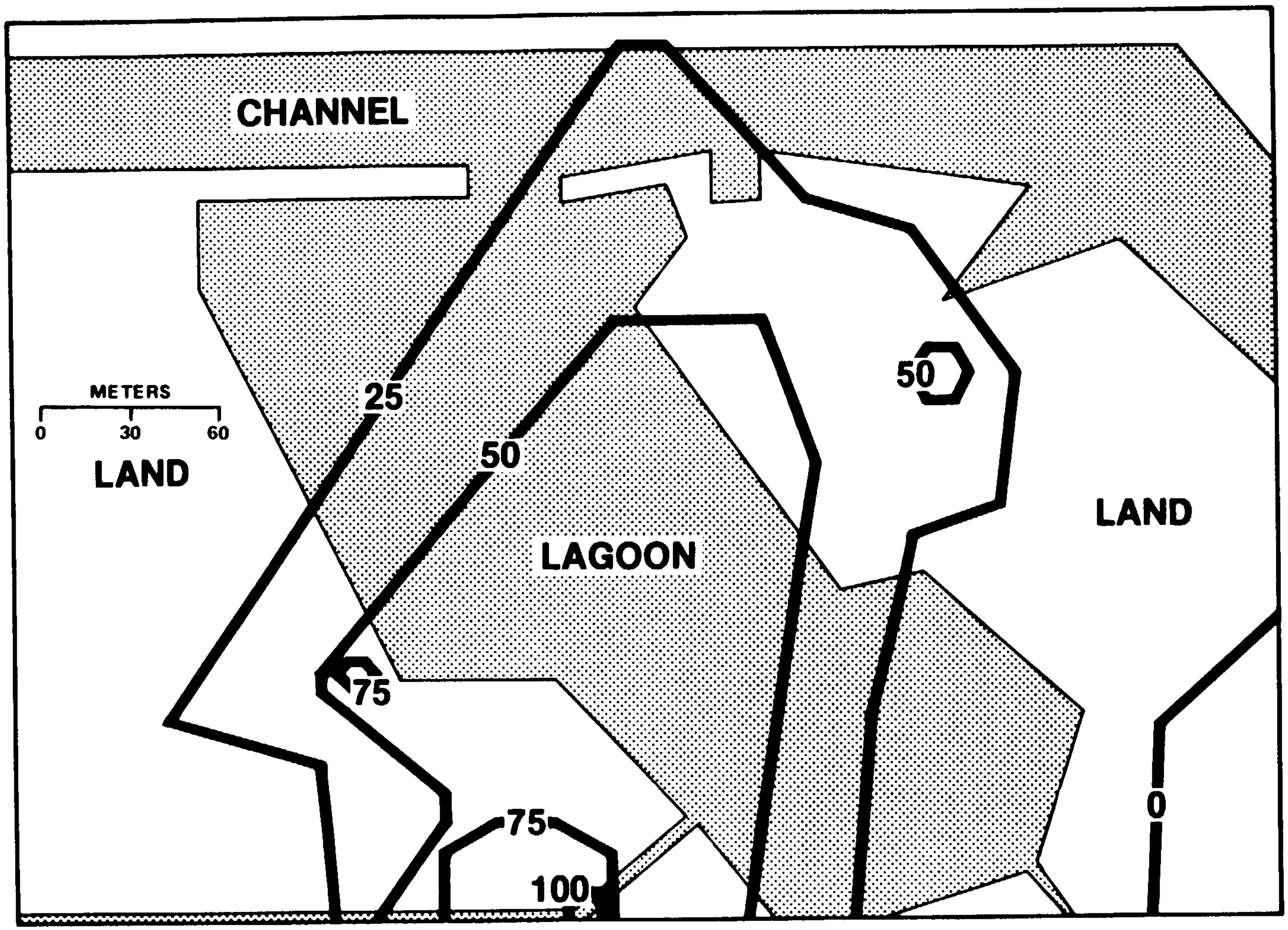

Figure 1. Isopleth map of chloride deposition in the near-field environment from STS-11 (41-B) (from Dreschel, Hall, and Hinkle 1985).

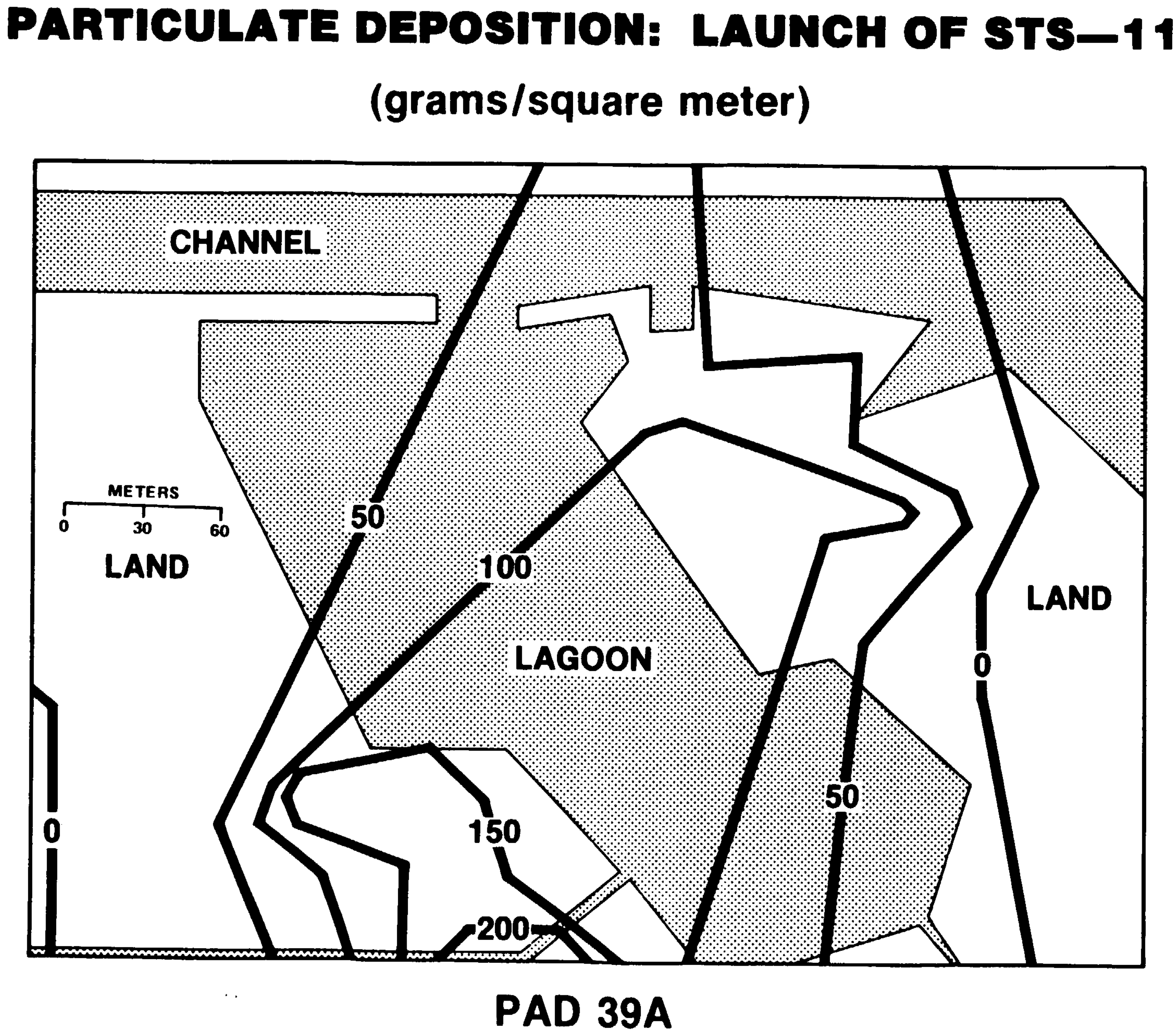

Figure 2. Isopleth map of particulate deposition in the near-field environment from STS-11 (41-B) (from Dreschel, Hall, and Hinkle 1985).

stronger surface winds, particularly if from the north (e.g., during STS-13), the ground cloud is blown off its usual path and the deposition pattern is different (Dreschel, Hall, and Hinkle 1985); the cloud may be blown south across the pad or east toward the ocean and deposition may occur in these areas.

Quantifying far-field deposition has proved difficult. The areas affected by far-field deposition are highly variable as shown by maps of cumulative launch deposition for STS-1 through STS-9 (Figure 3) and for the first 19 Shuttle launches, STS-1 through STS-51-F (Figure 4). This makes sampling of far-field deposition by deploying collectors difficult. Copper plates were used as deposition collectors for several early launches; however, only STS-2 produced deposition on more than a few plates in the far-field zone (Anderson and Keller 1983).

The Rocket Exhaust Effluent Diffusion Model (REEDM) was developed to predict launch cloud deposition. Earlier versions of this model (Bjorklund et al. 1982) predicted gaseous HCl (hydrogen chloride) concentration and aluminum oxide (Al_2O_3) concentration. Post-launch observations for many launches showed that this model correctly predicted direction of launch deposition but typically placed these effects much farther from the launch site than they actually occurred. In 1984, the model was modified to predict gravitational HCl (hydrochloric acid) deposition (Bowman et al. 1984). Results from the modified model are qualitatively reasonable; they predict higher deposition near the launch pad declining with distance.

The current study examines methods for estimating far-field deposition that can be compared to predictions of the REEDM program and are useful in assessing impacts of far-field deposition. Review of methods developed by Forest Service scientists for quantifying insecticide deposition (Barry et al. 1978) and past Shuttle launch studies (Anderson and Keller 1983) suggested that two methods should be evaluated for this purpose. In the first, vegetation receiving launch deposition was collected, the deposition washed off the leaves, and the washings subjected to chemical analyses. In the second method, drop counts were made of deposition on horizontal structures in the cloud path and deposition estimated from density and size of drops. Neither method required deploying sampling equipment in the path of the launch cloud.

METHODS

After each launch, a field team usually of two people was deployed to determine the track of launch cloud deposition. This determination was begun as soon after launch as safety and traffic considerations allowed. Output of the REEDM program was used to indicate the expected area of deposition. Other areas near the launch pad were also checked.

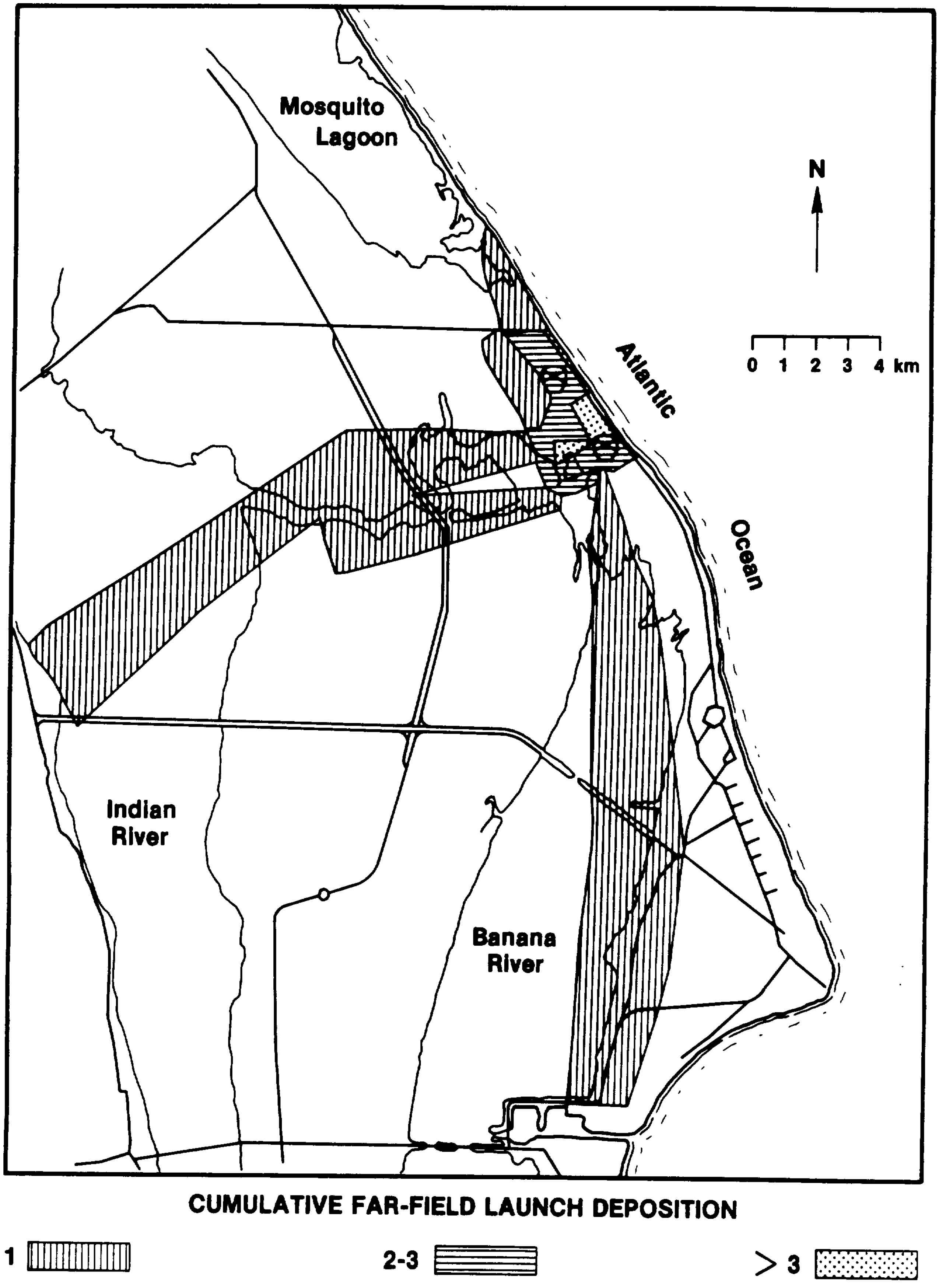

Figure 3. Cumulative far-field deposition from STS-1 through STS-9.

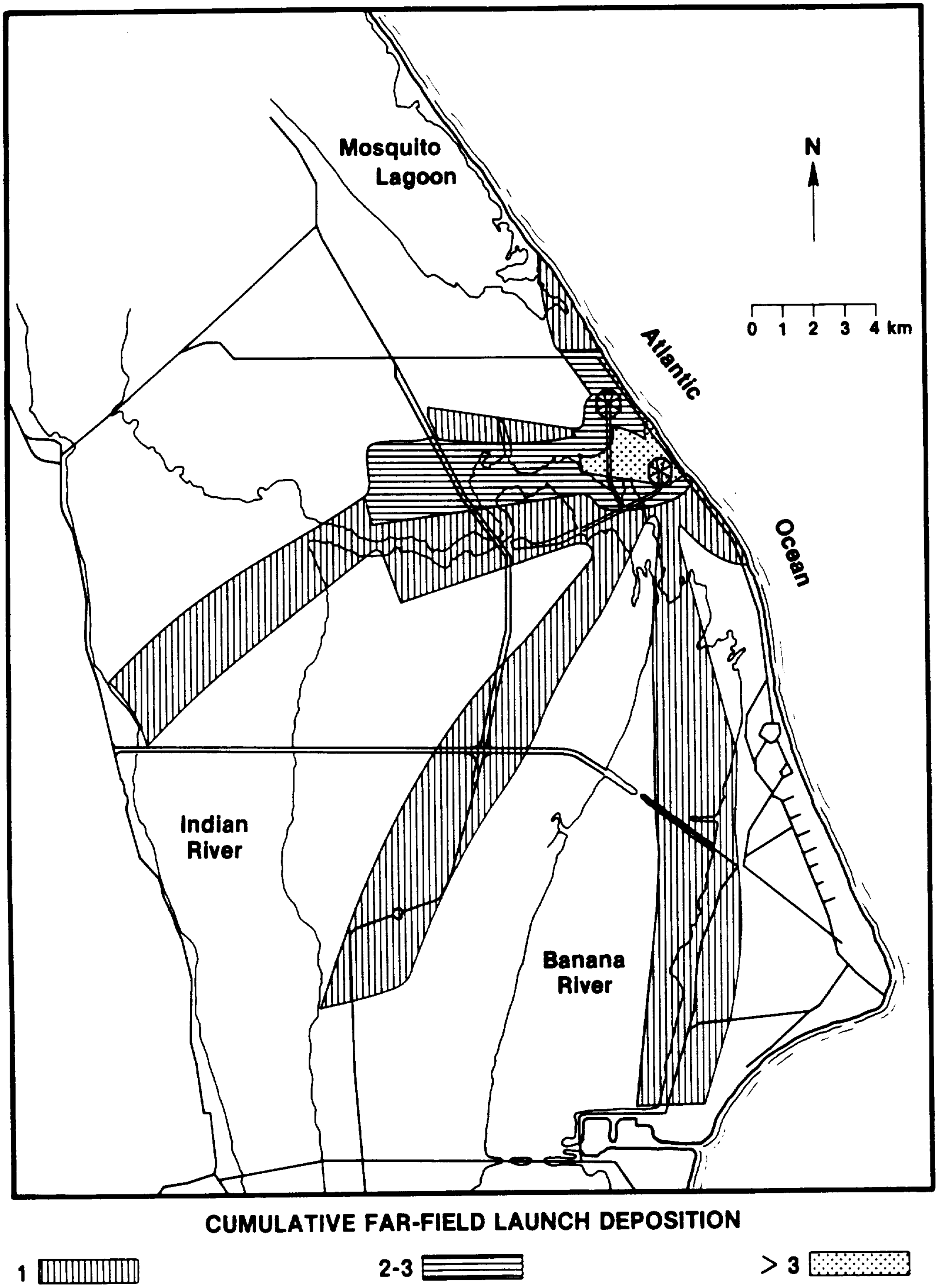

Figure 4. Cumulative far-field deposition from the first 19 launches, STS-1 through STS-51-F.

Structures and vegetation were examined for visible deposition in these areas. Locations of deposition were recorded on topographic quadrangle maps. Boundaries of deposition were determined by searching in a given direction until deposition could no longer be detected, or the cloud track moved out to sea, or otherwise could not be followed. Time required for the surveys varied with the path taken by the cloud. Most were completed either the day of launch or the next day.

Counts of deposition droplets were made at ten sites within the deposition path of STS-51-A (8 November 1984) (Figures 5, 6). Droplets were counted within defined areas on flat horizontal structures, pipelines, posts, dumpsters, metal plates, etc. At one site on Schwartz Road, a count was made on a vertical structure (sign) for comparison purposes. Droplet diameter was not measured for this launch. Observations were made on the relative size of droplets; the presence or absence of acid burning on vegetation was noted.

The launch of STS-51-F (29 July 1985) produced a deposition pattern west-northwest of Pad 39A and approached Pad 39B (Figures 7, 8). Estimates of chloride deposition were made for two sites along the Pad B Crawlerway (Sites F-1, F-2). Horizontal, flat surfaces at the parking lot south of the entrance to Pad B (Site F-1) and at a site (F-2) about 300 m south of there were sampled. Counts were made of spots produced by deposition on these surfaces. Diameters of the spots were measured. A formula developed by Anderson and Keller (1983) was used to calculate drop diameter from spot diameter. The formula is: $S = C + Bd^3$ where S = spot diameter (mm), d = drop diameter (mm), C = 0.084634 mm, and B = 8.72976 mm^{-2}.

Given the drop diameter, d, volume was calculated as $V = \pi d^3/6$. From drop volume and mean drop number, the volume of deposition per m^2 was calculated. Chloride deposition per m^2 was calculated assuming each droplet to be 2 normal HCl (74 mg Cl^-/ml), a worst case estimate.

Leaf samples were collected from two launches, STS-51-D (12 April 1985) and STS-51-B (29 April 1985). Leaf samples from STS-51-D were collected from five locations, three impacted by launch and two control sites. These were: State Road 3 near the KSC Weather Station (Site D-1) (*Salix caroliniana*, willow) which received light deposition, Pad B Crawlerway near the pump station (Site D-2) (willow) which received moderate deposition, NASA Causeway near the Banana River (Site D-3) (willow) which was a control site, Dike Road north of Pad 39A (Site D-4) (*Baccharis halimifolia*, groundsel) which received heavy deposition, and the area west of North Cape Road just south of Pad 39A (Site D-5) (groundsel) which was a second control site (Figures 9, 10).

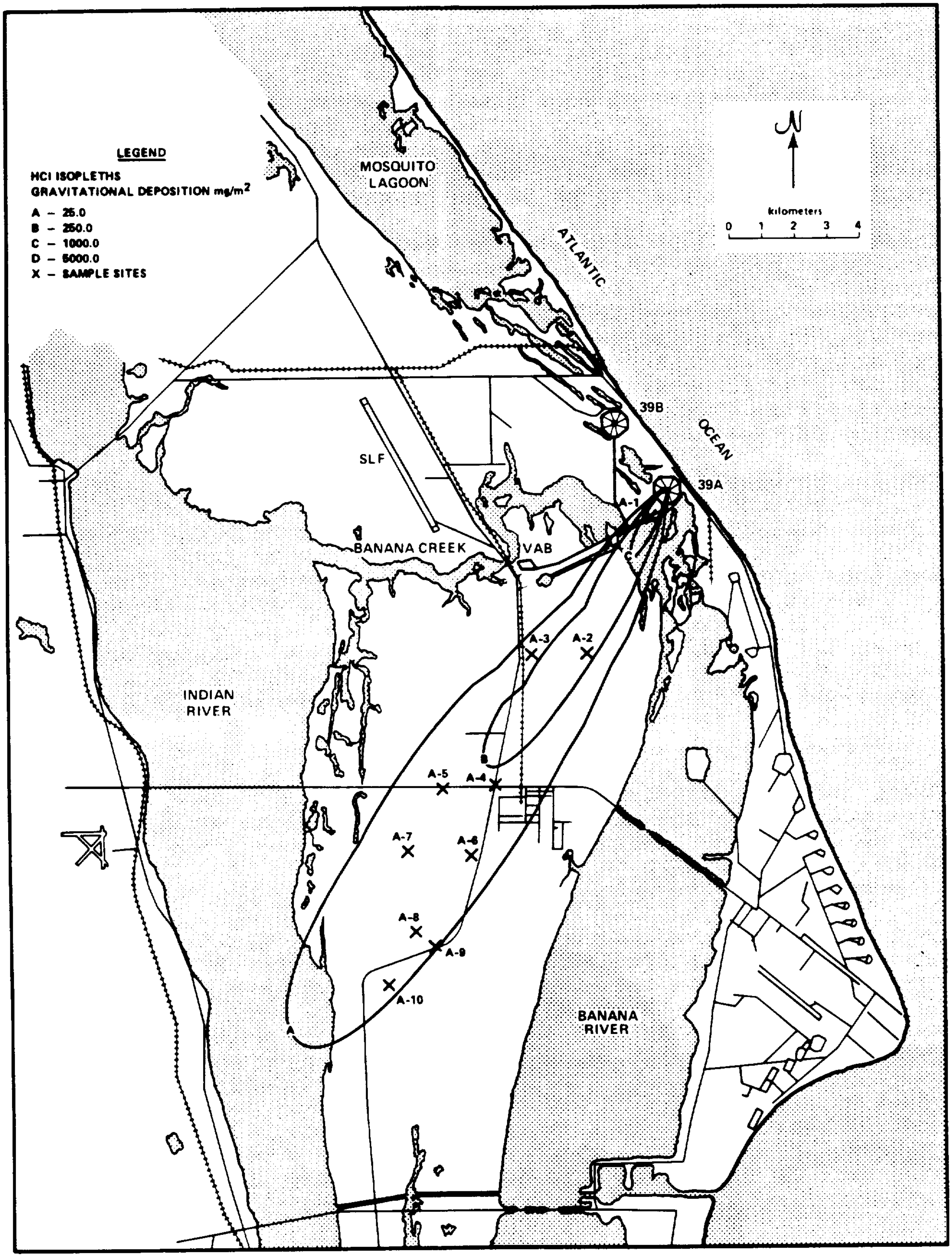

Figure 5. Rocket Exhaust Effluent Diffusion Model (REEDM) preditions for STS-51-A (t-o).

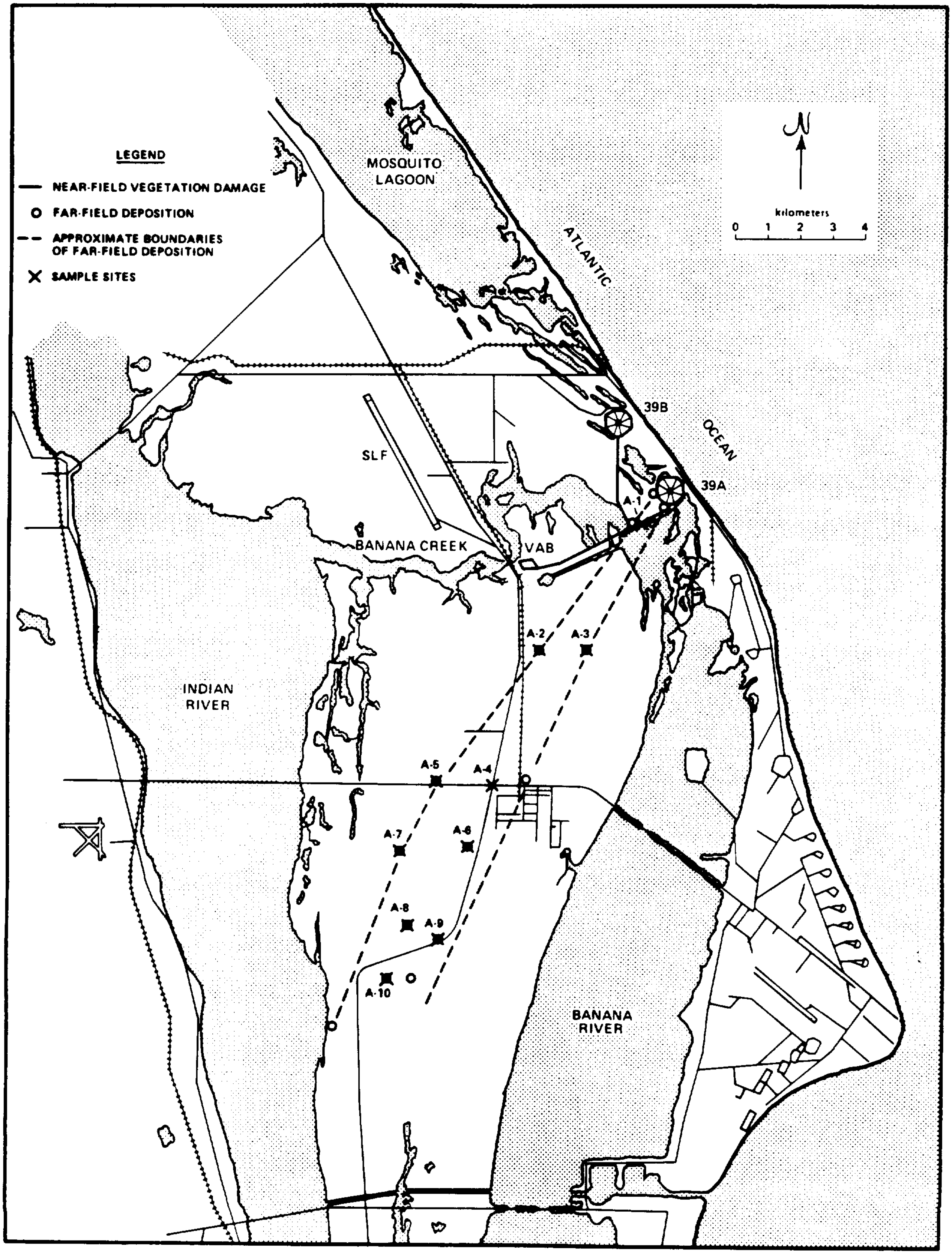

Figure 6. Launch cloud path of STS-51-A based on ground observations. See Table 2 for site locations.

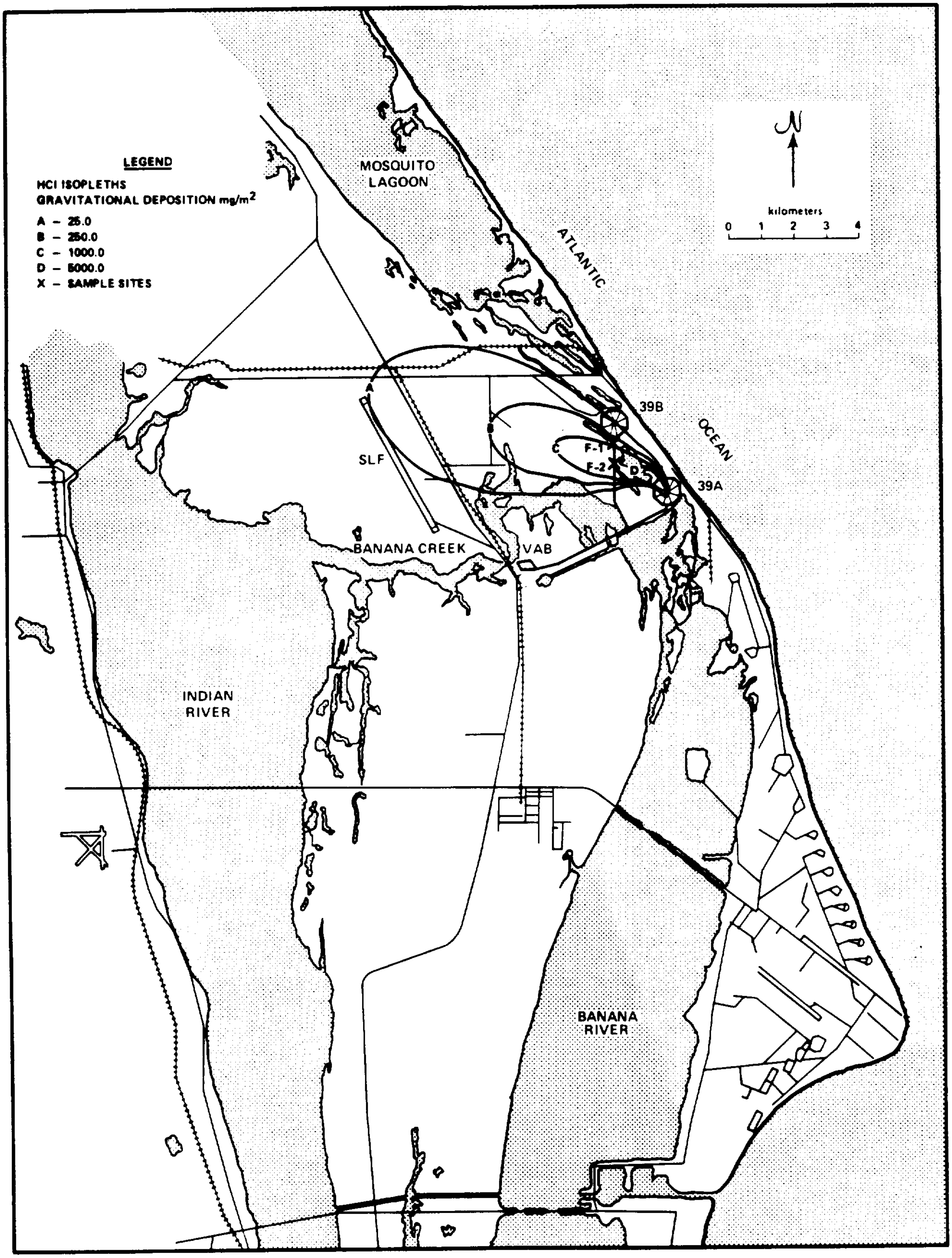

Figure 7. Rocket Exhaust Effluent Diffusion Model (REEDM) predictions for STS-51-F (t-o).

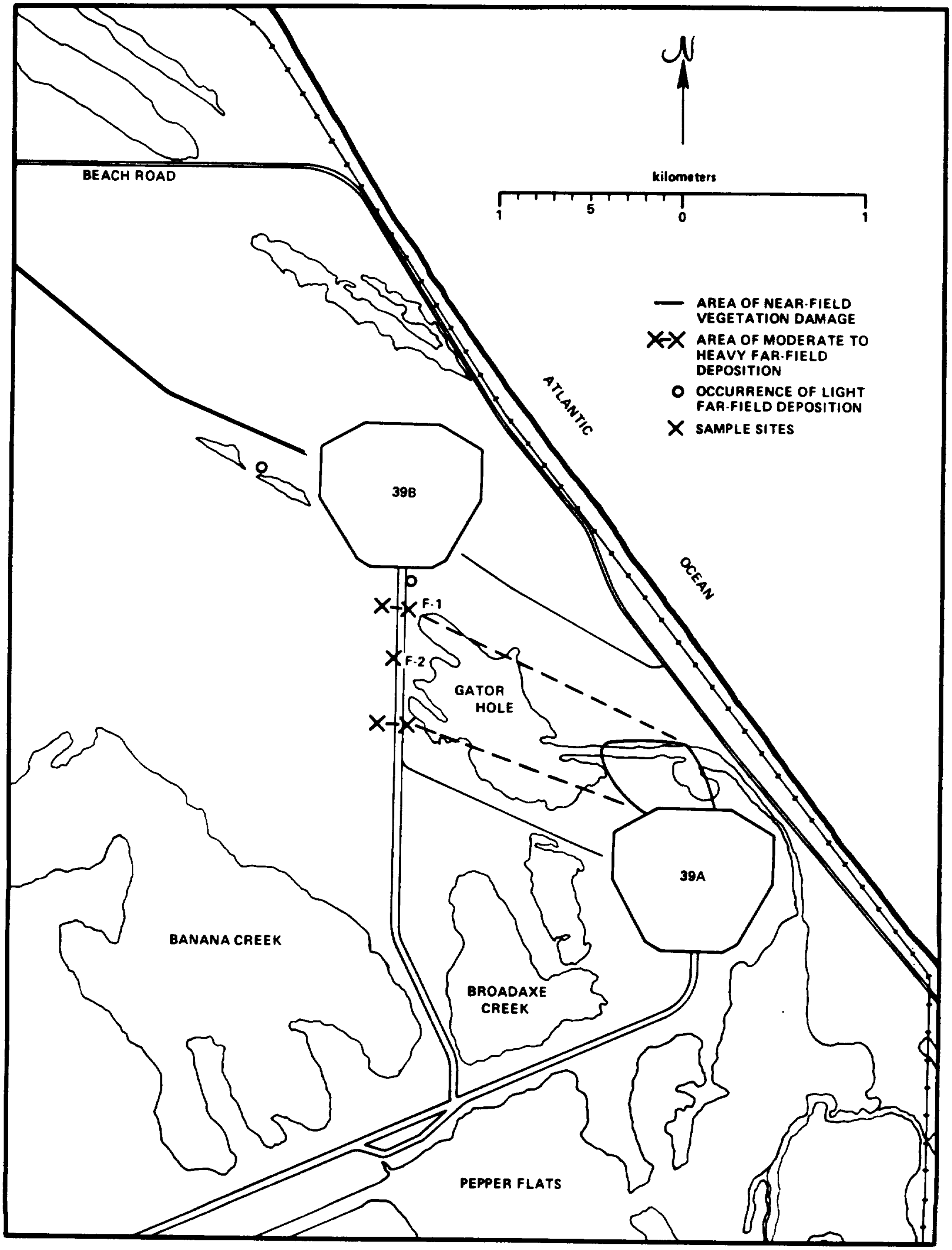

Figure 8. Launch cloud path of STS-51-F based on ground observations. See text for site locations.

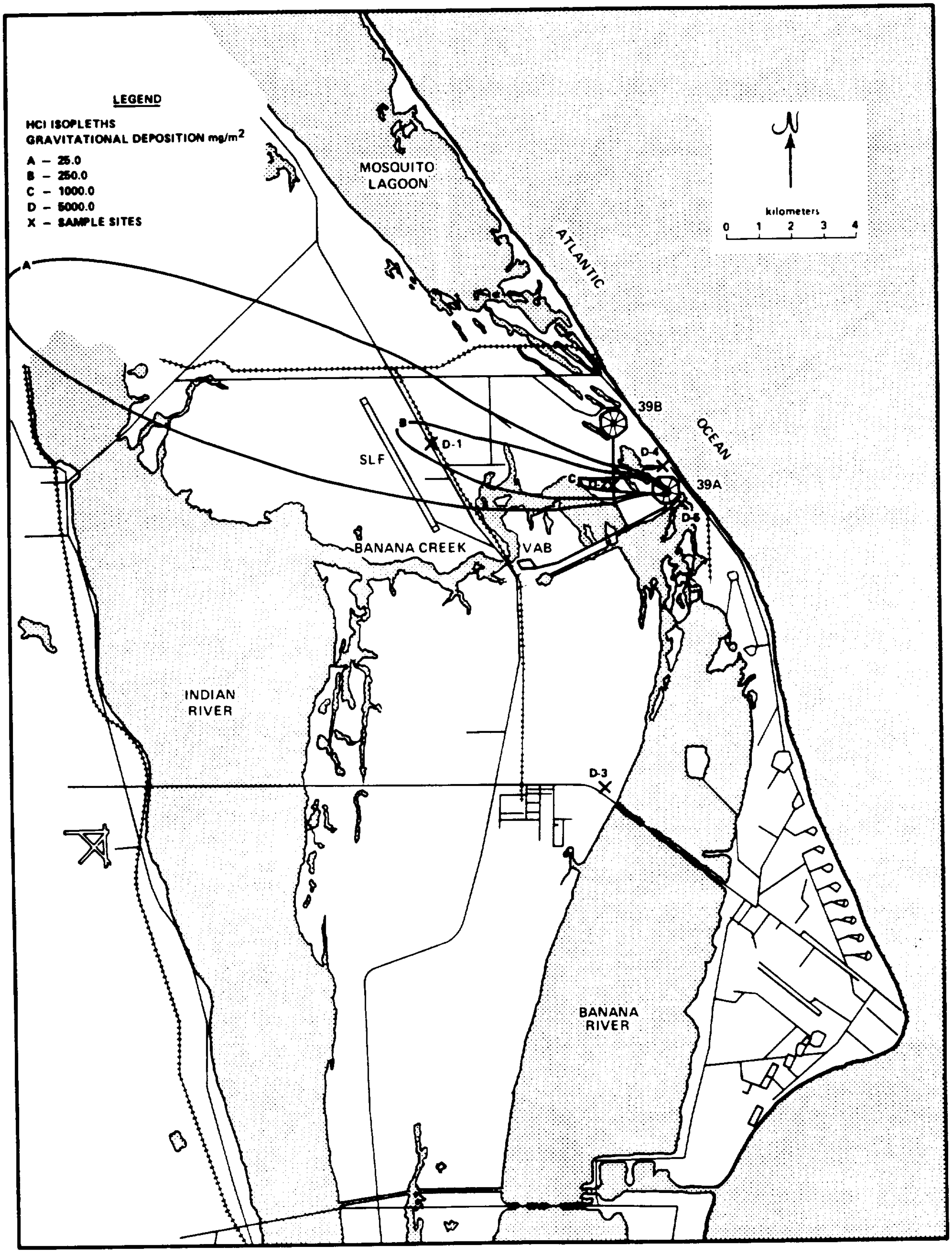

Figure 9. Rocket Exhaust Effluent Diffusion Model (REEDM) predictions for STS-51-D (t-o).

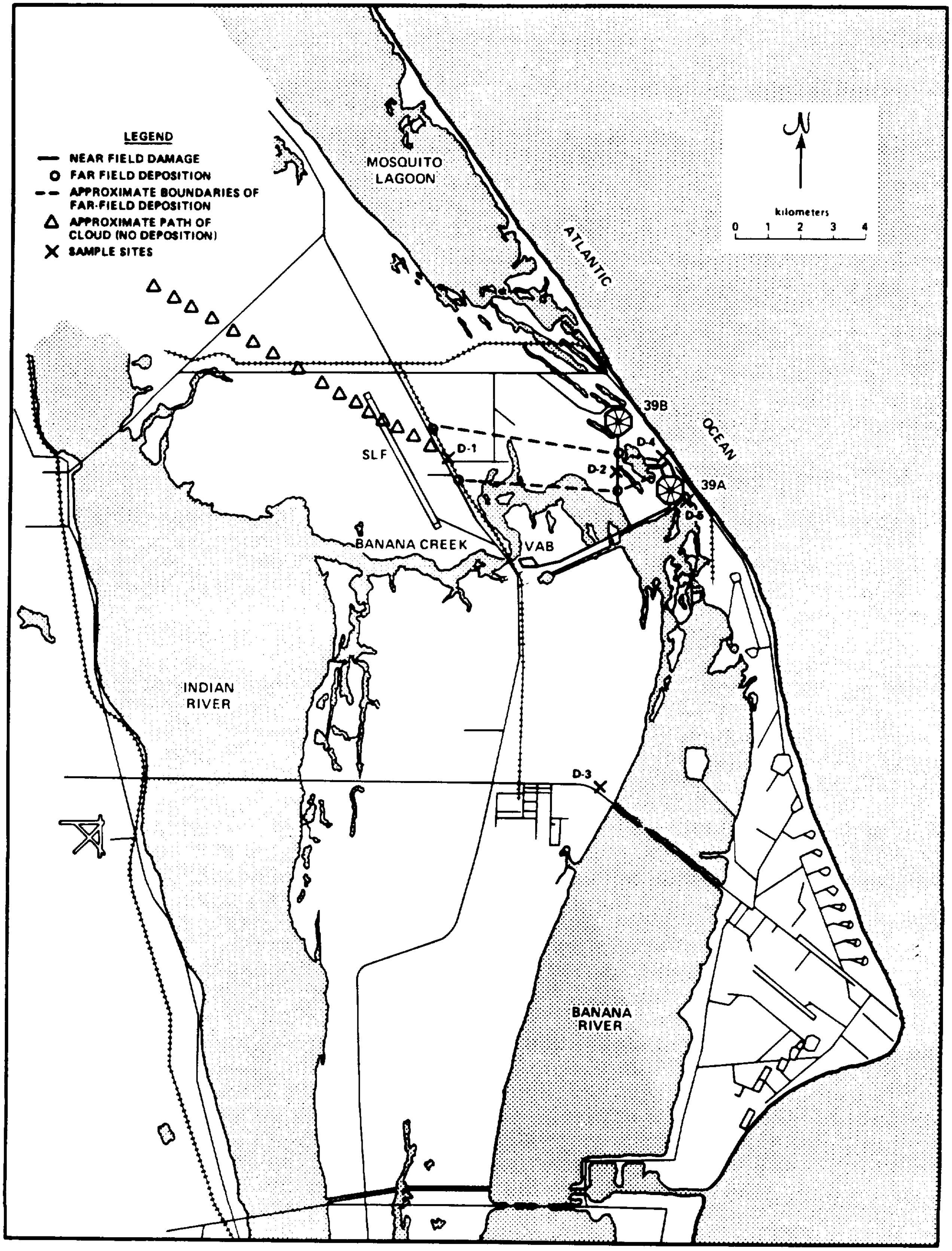

Figure 10. Launch cloud path of STS-51-D based on ground observations. See text for site locations.

Leaf samples from STS-51-B were also collected from five sites: south of Pad 39A near Saturn Causeway (Site B-1) (*Typha* sp., cattail) which received heavy deposition, south of Pad 39A near the eastern boundary of deposition (Site B-2) (groundsel) which received light deposition, south of Pad 39A near the center of the observed deposition (Site B-3) (groundsel) which received heavy deposition, just west of North Cape Road south of Pad 39A (Site B-4) (groundsel) which was a control site, and Static Test Road (Site B-5) (cattail) which was a second control site (Figures 11, 12).

Leaf collections were made in duplicate from most study sites receiving launch deposition from STS-51-D and STS-51-B. Leaves were collected from the outer portion of the plant canopy. Branches of shrubs and blades of cattail were clipped and placed in zip-lock bags. Samples were returned to the laboratory. Leaves of willow and groundsel were removed from the branches with a forceps and placed in Nalgene bottles. Sections of the cattail leaves were cut and placed in bottles. To each bottle, 150 ml of deionized water were added. Samples were shaken virgorously for two minutes by hand. Leaf samples were then removed from the bottles using forceps. Leaves were placed in a plant press and dried overnight at 50°C in a forced air drying oven. Leaf areas of these samples were determined using a LICOR Model 3100 Area Meter. Leaves were examined under a Bausch & Lomb binocular microscope (7X - 30X) before and after washing to determine if deposition was visible.

The leaf washings were analyzed for chloride (Cl^-) and aluminum (Al^{2+}). Chloride analysis used an Orion ion specific electrode (Orion application procedure no. 507) (Orion Research, Inc. 1982). Aluminum analysis used a Perkin-Elmer Model 3030 Atomic Absorption Spectrophotometer (Perkin-Elmer methods #13.1) (Perkin-Elmer Corporation 1982).

Volume of the washings and the concentration of chloride and aluminum were used to calculate the amount of these materials washed from the leaf subsamples. Amount of chloride or aluminum per unit area (mg/m^2) was calculated from the amounts washed from the leaves and the area of the leaf subsamples that were washed. Deposition was estimated by subtracting the control site values of chloride and aluminum from the values of the sites receiving deposition.

In order to compare estimates of far-field deposition from drop counts and from leaf collections, both methods were employed for the launch of STS-61-B (26 November 1985). Leaf samples were collected from six locations, four impacted by launch and two control sites. These were Pad B Road (Site 6B-1) (*Myrica cerifera*, wax myrtle) which was a control site, Pad B Road (Site 6B-2) (groundsel), a second control site, center section of the

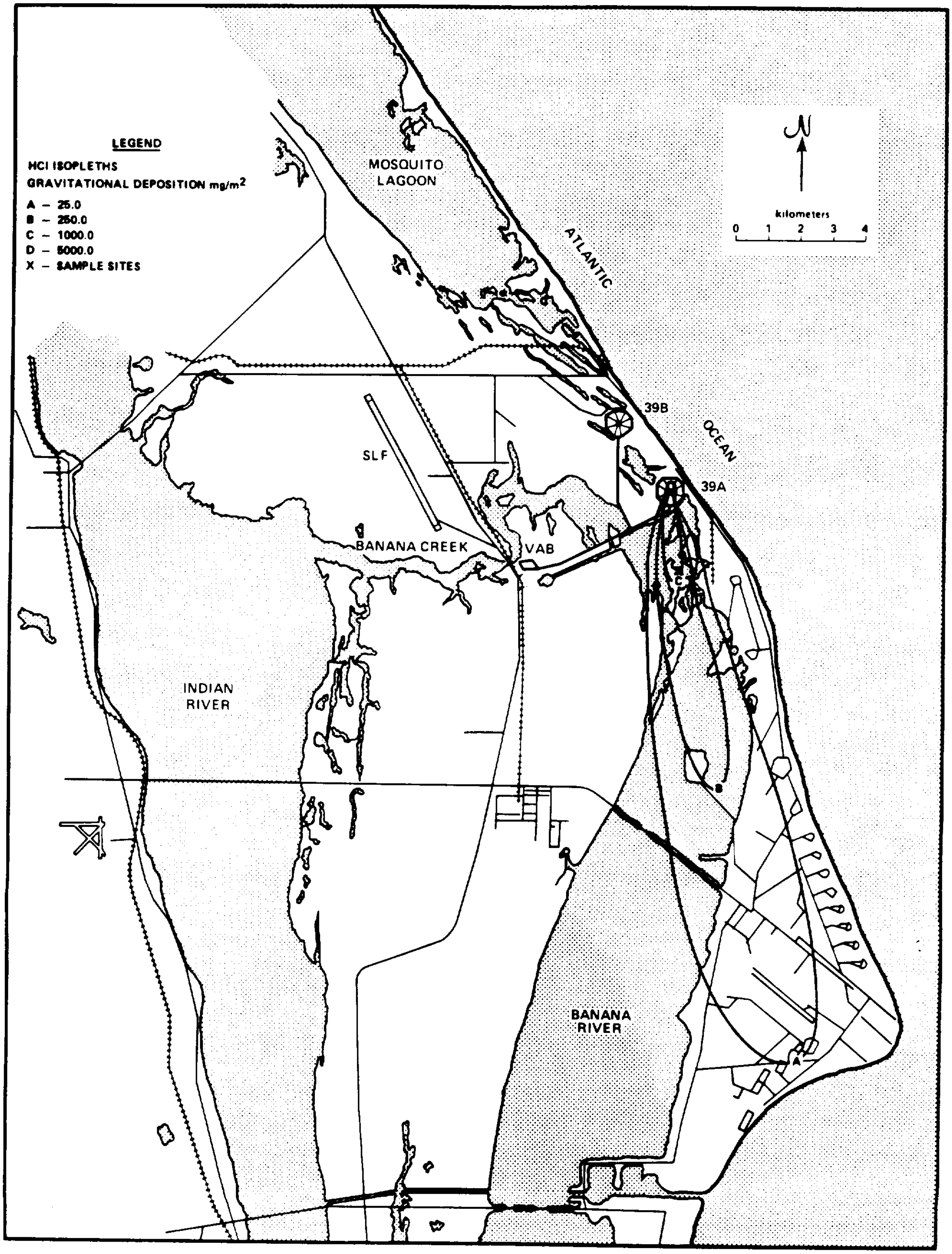

Figure 11. Rocket Exhaust Effluent Diffusion Model (REEDM) predictions for STS-51-B (t-o).

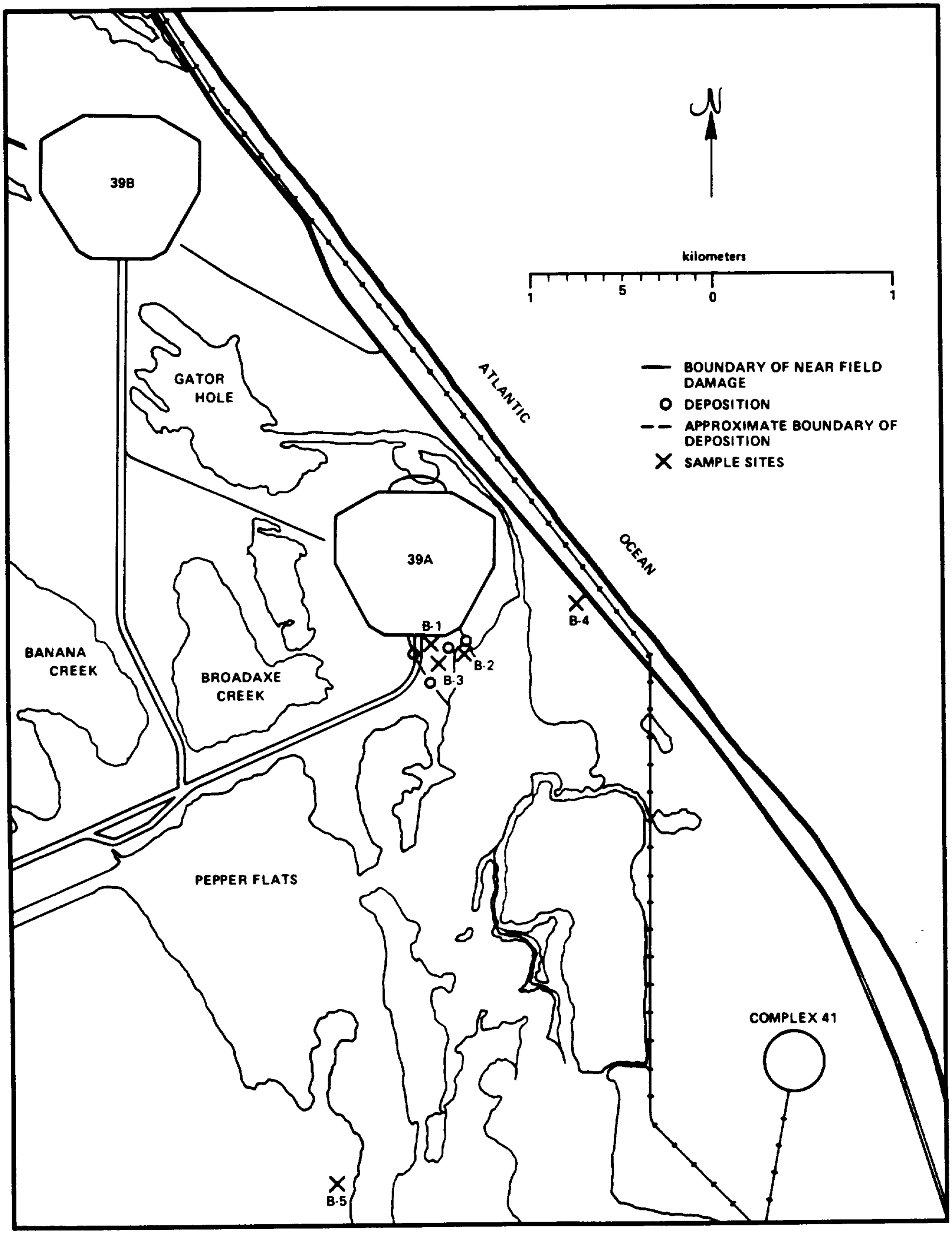

Figure 12. Launch cloud path of STS-51-B based on ground observations. See text for site locations.

Dike Road (Site 6B-3) (groundsel) which received heavy deposition, along the southeast side of Pad 39B (Site 6B-4) (wax myrtle) which received moderate deposition, south of Pad 39B along the Crawlerway (Site 6B-5) (wax myrtle) which received light deposition, and the west end of the Dike Road (Site 6B-6) (wax myrtle) which received light deposition (Figures 13, 14).

Drop counts and size estimates were made on horizontal structures at Sites 6B-4 and 6B-5.

Chloride and aluminum deposition were determined for leaf samples; chloride deposition only was calculated for drop counts as previously described.

RESULTS

Meterological conditions for the five launches are given in Table 1. Isopleths of predicted HCl gravitational deposition from the REEDM program are given in Figures 5, 7, 9, 11, and 13. Observed patterns of launch deposition are summarized in Figures 6, 8, 10, 12, and 14.

Droplet counts for STS-51-A are given in Table 2. Droplet density was greater near the center of the cloud track than toward the edges. Drop size was observed to decrease with distance from the launch pad. Acid deposition extended as far as NASA Causeway, 10.8 km from the launch pad. Farther south only dry deposition was seen; no acid burning of leaves was detected. Near the southern end of the cloud track (Sites A-9, A-10, Figures 5, 6), 17.7 km from the pad, drop density (drops/m^2) reached its highest levels. However, these drops were very small. Some deposition occurred south of these sites but it was very light and the minute size of the droplets made detection difficult. Comparisons of horizontal and vertical collectors at Site A-3 indicated that horizontal surfaces had much higher drop counts than vertical ones, as expected (Table 2).

Calculated chloride deposition for Sites F-1 and F-2 (STS-51-F) is given in Table 3. Site F-2 is within the C isopleth predicted by the REEDM program (Figures 7, 8) with an expected deposition of 1000 mg/m^2; the calculated deposition (89 mg/m^2) is much less. Site F-1 is within the B isopleth (Figures 7, 8) with an expected deposition of 250 mg/m^2; the calculated deposition of 185 mg/m^2 is similar.

Microscopic examination of leaf samples collected from STS-51-D and STS-51-B prior to leaf washing showed obvious deposition on the leaf surfaces. After washing, deposition could not be detected microscopically.

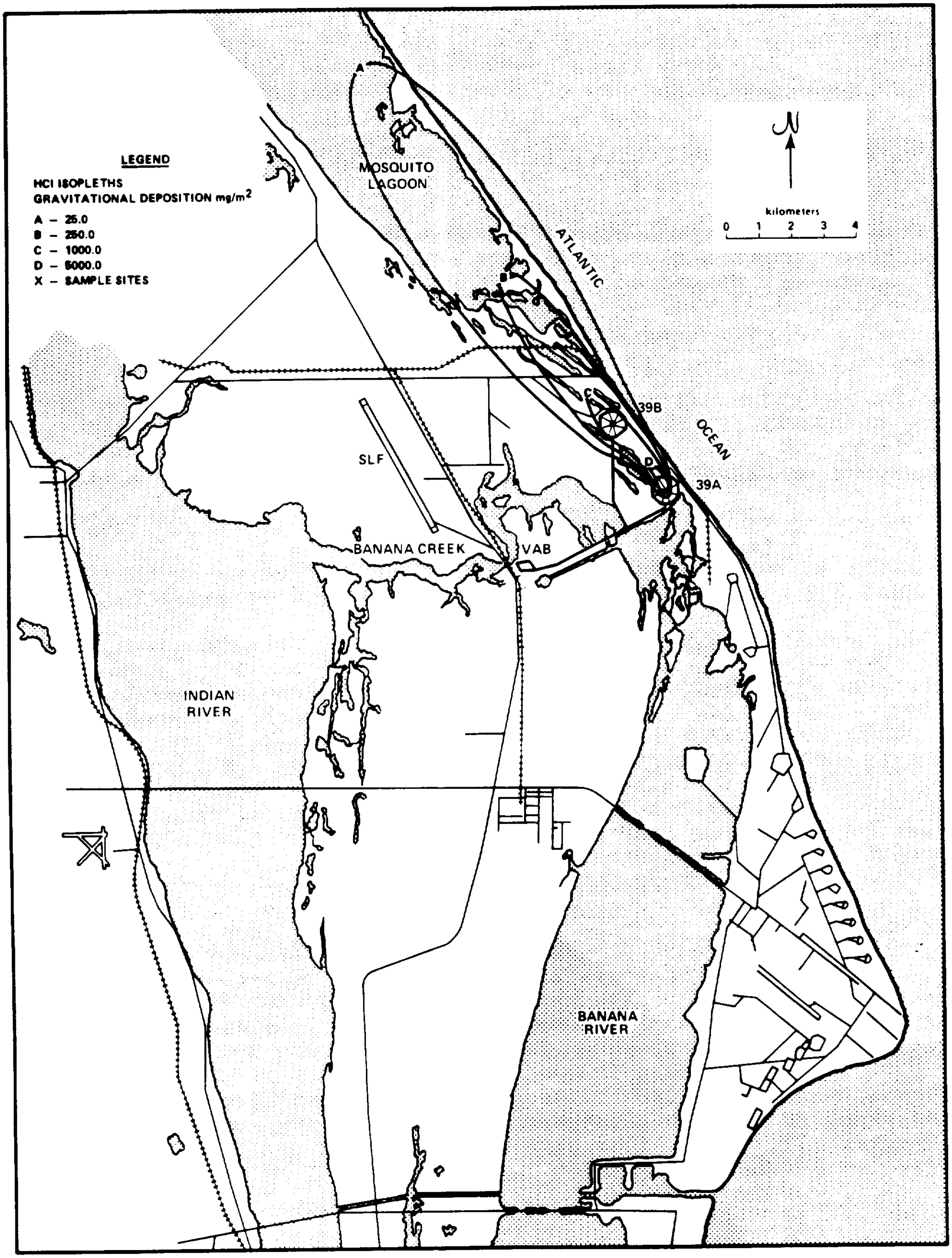

Figure 13. Rocket Exhaust Effluent Diffusion Model (REEDM) predictions for STS-61-B (t-o).

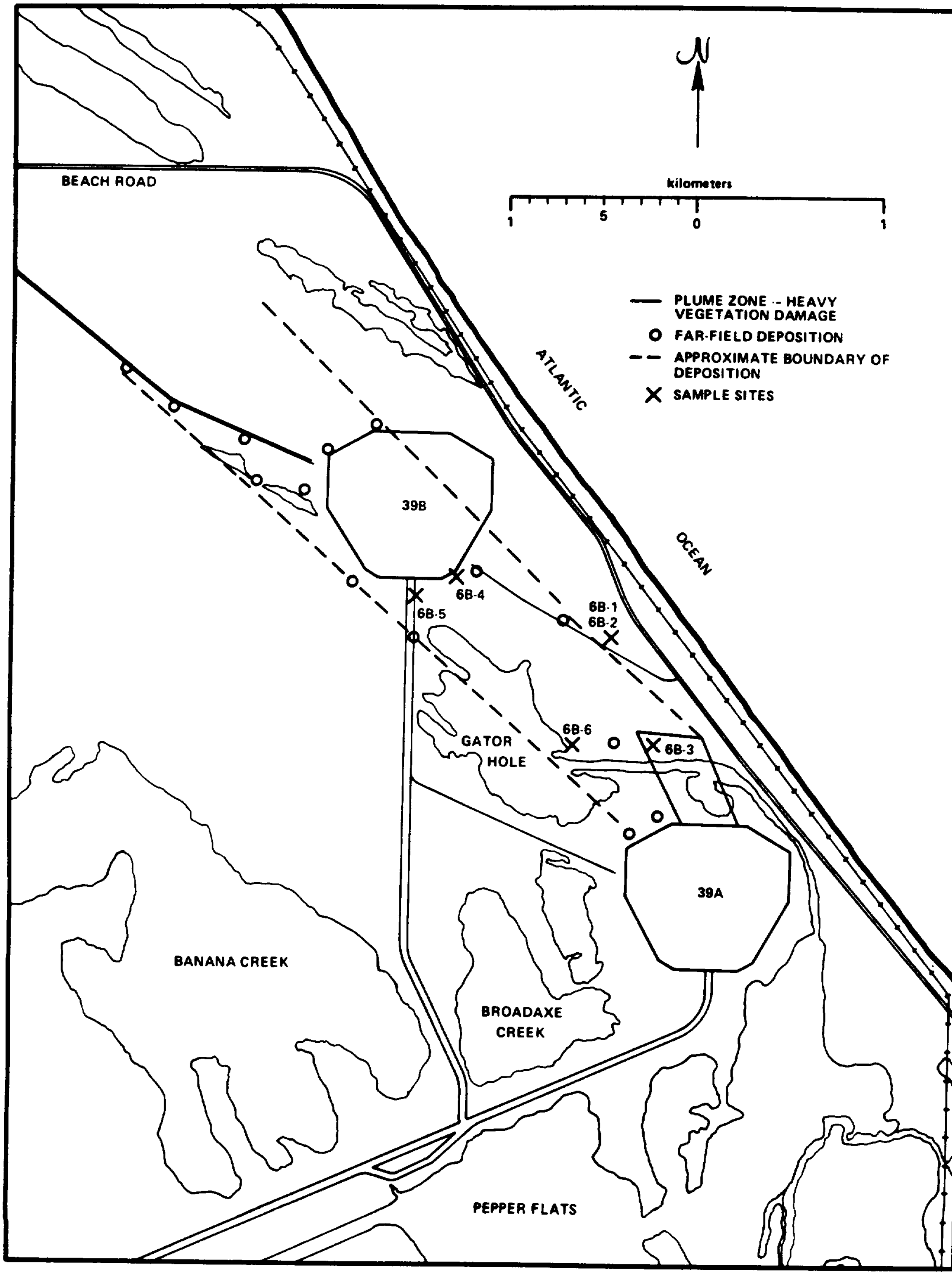

Figure 14. Launch cloud path of STS-61-B based on ground observations. See text for site locations.

Table 1. Meterological conditions for the five Space Shuttle launches.

LAUNCH	DATE	TIME	TEMPERATURE (°C)	SURFACE WIND DIRECTION (DEGREE)	SURFACE WIND SPEED (m/s)	RELATIVE HUMIDITY (%)
51-A	11/8/84	0718	19.3	20.0	3.60	59.0
51-D	4/12/85	0859	19.8	80.0	5.14	68.0
51-B	4/29/85	1204	24.9	360.0	6.69	58.0
51-F	7/29/85	1523	29.2	120.0	3.09	73.0
61-B	11/26/85	1929	18.9	135.0	1.03	96.0

Table 2. Density of droplet deposition from STS-51-A at various sites[1].

Site Number	Site Description	Number of Drops per m^2 Mean	Number of Drops per m^2 Range
A-1	Crawlerway	2312	1447-2997
A-2	Schwartz Road at Camera Pad	3286	1550-5477
A-3	Schwartz Road at VIP Viewing Site	5747	5042-6465
A-3	Schwartz Road at VIP Viewing Site (Vertical Structure)	362	310-413
A-4	State Route 3 at Intersection with NASA Causeway	2722	1685-4018
A-5	State Route 3 at Visitors Information Center	519	384-778
A-6	Ransom Road at Excess Property Site	4147	2203-5573
A-7	Ransom Road at S-Band Site	421	259-648
A-8	Jerome Road at West End	1361	648-2333
A-9	State Route 3 at South Gate	5832	3240-9072
A-10	Crisafulli Road	7776	7776

[1]See Figure 6 for site locations.

Table 3. Far-field chloride deposition from STS-51-F calculated from drop counts.

Site[1]	Density of Deposition Spots (spots/m^2)	Spot Diameter Mean (mm)	Spot Size Range (mm)	Drop Diameter Mean (mm)	Calculated[2] Chloride Deposition (mg/m^2)	Model[3] Prediction (mg/m^2)
F-1	25263	1.75	0.5-2.0	0.5756	185	200
F-2	41073	0.57	0.25-1.0	0.3817	74	1000

[1]See Figure 8 and text for site locations.
[2]Calculated using methods of Anderson and Keller (1983). See text for details.
[3]Predicted deposition based on isopleth map from Rocket Exhaust Effluent Diffusion Model (REEDM).

Chloride deposition from STS-51-D determined from leaf collections is summarized in Table 4. The two areas of light to moderate deposition (Sites D-1 and D-2) had similar amounts of chloride deposition, about 26 to 67 mg/m^2. Site D-1 (6.9 km from the pad) was predicted to be within the B isopleth (250 mg/m^2) by the REEDM program (Figure 9); however observations showed that it was at the edge of observable deposition (Figure 10). Site D-2 (1.7 km from the pad) was predicted to be within the C isopleth (1000 mg/m^2) (Figure 9) by the REEDM program but did not differ from site D-1 in chloride deposition.

The Dike Road site (D-4) received heavy chloride deposition (Table 4). This site was in the plume zone from the launch not in an area predicted by the REEDM program. The model did predict a maximum chloride deposition of 9175 mg/m^2 at 400 m from Pad A decreasing to 1578 mg/m^2 at 1500 m from the pad. Site D-4 is about 800 m from the center of Pad 39A and the predicted values bracket the observed ones of 1622 to 2215 mg/m^2 chlorides.

Aluminum deposition on leaf surfaces from STS-51-D is summarized in Table 5 (see also Figure 10). Aluminum deposition was considerably higher at Site D-2 (1.7 km from Pad 39A) than D-1 (6.9 km from Pad 39A) even though chlorides were similar at these two sites. Aluminum deposition along the Dike Road (Site D-4) was much higher than at the other sites. Aluminum deposition is not predicted by standard runs of the current version of the REEDM program; however, the aluminum results are consistent with the observed pattern of deposition.

Chloride deposition from STS-51-B is summarized in Table 6. Site B-1 had high deposition rates. This site was about 450 m south of the center of Pad 39A (Figure 12). Maximum chloride deposition predicted by the REEDM program was 6722 mg/m^2 at 400 m from the pad at bearing 179°; this is in general agreement with the deposition amounts (4246 mg/m^2 - 5303 mg/m^2) collected from leaf samples at this site. Away from the center line, deposition declined, as at Site B-3, but was still readily detected. At the edge of the deposition pattern (Site B-2), chloride deposition could not be detected (Table 6). Deposition could not be detected in areas within the A and B isopleths (Figures 11, 12) such as sites along Static Test Road or on Cape Canaveral Air Force Station.

Aluminum deposition from STS-51-B is summarized in Table 7 (see also Figure 12). Aluminum levels were highest at Site B-1 (450 m south of Pad 39A), somewhat lower at Site B-2 (off the center-line), and much lower, though still detectable, at Site B-3 (edge of deposition). Aluminum was well above background levels at Site B-3 although chloride deposition was not detectable.

Table 4. Far-field chloride deposition from STS-51-D determined from leaf samples.

Site[1]	Species	Amount of Chloride in Washings (mg)	Leaf Area (cm^2)	Amount of Chloride per Unit Area (mg/m^2)	Chloride[2] Deposition (mg/m^2)	Model[3] Prediction (mg/m^2)
D-1	Willow #1	.81	68.9	117.56	67.40	250
D-2	Willow #1	.87	92.6	93.95	43.79	1000
D-2	Willow #2	1.32	174.1	75.82	25.66	1000
D-3	Willow #1 (control)	0.62	123.6	50.16	----	0
D-4	Groundsel #1	12.58	72.6	1732.78	1622.29	N/A
D-4	Groundsel #2	26.40	113.5	2325.99	2215.50	N/A
D-5	Groundsel #1 (control)	1.58	143.0	110.49	----	0

[1]See Figure 10 and text for site locations.
[2]Deposition calculated as amount per unit area minus control for that species.
[3]Predicted deposition based on isopleth map from Rocket Exhaust Effluent Diffusion Model (REEDM).

Table 5. Far-field aluminum deposition from STS-51-D determined from leaf samples.

Site[1]	Species	Amount of Aluminum in Washings (mg)	Leaf Area (cm^2)	Amount of Aluminum per Unit Area (mg/m^2)	Aluminum[2] Deposition (mg/m^2)
D-1	Willow #1	0.01	68.9	1.45	0.64
D-2	Willow #1	0.03	92.6	3.24	2.43
D-2	Willow #2	0.06	174.1	3.45	2.64
D-3	Willow #1 (control)	0.01	123.6	0.81	----
D-4	Groundsel #1	0.61	72.6	84.02	83.32
D-4	Groundsel #2	1.23	113.5	108.37	107.67
D-5	Groundsel #1 (control)	0.01	143.0	0.70	----

[1]See Figure 10 and text for site locations.
[2]Deposition calculated as amount per unit area minus control for that species.

Table 6. Far-field chloride deposition from STS-51-B determined from leaf samples.

Site[1]	Species	Amount of Chloride in Washings (mg)	Leaf Area (cm^2)	Amount of Chloride per Unit Area (mg/m^2)	Chloride[2] Deposition (mg/m^2)	Model[3] Prediction (mg/m^2)
B-1	Cattail #1	60.06	125.7	4778.04	4245.96	6722
B-1	Cattail #2	82.92	142.1	5835.33	5303.25	6722
B-2	Groundsel #1	2.04	132.4	154.08	----	1000
B-2	Groundsel #2	1.36	114.7	118.57	----	1000
B-3	Groundsel #1	15.53	132.6	1171.19	922.64	1000
B-3	Groundsel #2	16.07	168.8	952.01	703.46	1000
B-4	Groundsel (control)	4.28	172.2	248.55	----	0
B-5	Cattail (control)	4.81	90.4	532.08	----	0

[1]See Figure 12 and text for site locations.
[2]Deposition calculated as amount per unit area minus control for that species.
[3]Predicted deposition based on Rocket Exhaust Effluent Diffusion Model (REEDM), maximum centerline calculations used for Site B-1 and isopleth map for other sites.

Table 7. Far-field aluminum deposition from STS-51-B determined from leaf samples.

Site[1]	Species	Amount of Aluminum in Washings (mg)	Leaf Area (cm^2)	Amount of Aluminum per Unit Area (mg/m^2)	Aluminum[2] Deposition (mg/m^2)
B-1	Cattail #1	0.58	125.7	46.14	43.93
B-1	Cattail #2	0.70	142.1	49.26	47.05
B-2	Groundsel #1	0.06	132.4	4.53	3.37
B-2	Groundsel #2	0.05	114.7	4.36	3.20
B-3	Groundsel #1	0.38	132.6	28.66	27.50
B-3	Groundsel #2	0.69	168.8	40.88	39.72
B-4	Groundsel (control)	0.02	172.2	1.16	----
B-5	Cattail (control)	0.02	90.4	2.21	----

[1]See Figure 12 and text for site locations.
[2]Deposition calculated as amount per unit area minus control for that species.

Chloride deposition from STS-61-B is summarized in Table 8. Site 6B-3 had the highest deposition rates. This site was about 900 m north of the center of Pad 39A (Figure 14). Maximum chloride deposition predicted by the REEDM program was 14900 mg/m^2 at 400 m from the pad at bearing 338° and 2800 mg/m^2 at 1400 m from the pad at bearing 328°. The observed deposition of 2163 mg/m^2 to 2616 mg/m^2 is near this range. Farther from the pad and towards the edge of the deposition path, the amount of deposition declined as at Sites 6B-4 (Pad 39B) and 6B-5 (Pad B Crawlerway). Chloride deposition could not be detected at Site 6B-6 (Dike Road, west) although light deposition was visible.

Aluminum deposition from STS-61-B is summarized in Table 9 (see also Figure 14). Aluminum deposition was highest at Site 6B-3, 900 m north of Pad 39A. Aluminum deposition declined farther from the launch pad but was still detectable though very low at Site 6B-6 (Dike Road, west).

Chloride deposition calculated from drops counts is given in Table 10. That calculated for Site 6B-4 (Pad 39B) (187.2 mg/m^2) is more than given by the leaf samples (65.6 mg/m^2 - 98.0 mg/m^2); the calculated value for Site 6B-5 (Pad B Crawlerway) (28.1 mg/m^2) is close to that from one leaf sample (36.0 mg/m^2).

Ratios of aluminum to chloride in the deposition samples were calculated (Table 11). Aluminum ranged from about 1% to 10% of the chloride amounts washed from the same leaf sample except for samples from two sites (6B-4 and 6B-5) from the launch of STS-61-B.

DISCUSSION

Comparisons of the REEDM program isopleth predictions and ground observations show general qualitative agreement in terms of direction of the cloud path and magnitude of deposition. The exception to this is the near-field deposition area north of Pad 39A. This area is impacted before the cloud rises to stabilization height. Deposition in this area ranges to 100 g/m^2 of chlorides or more while the maximum deposition predicted by the REEDM program is on the order of 5000-15000 mg/m^2 (5.0-15.0 g/m^2). Deposition can not always be visually detected as far downfield as the model predicts. In three of the five launches examined here, the A isopleth (25 mg/m^2) could not be detected on the ground.

The drop counts made for STS-51-A provide some indication of launch deposition. Within a given area, counts were typically higher near the centerline of the cloud track than toward the edges as predicted by the model. However, since drop size

Table 8. Far-field chloride deposition from STS-61-B determined from leaf samples.

Site[1]	Species	Amount of Chloride in Washings (mg)	Leaf Area (cm^2)	Amount of Chloride per Unit Area (mg/m^2)	Chloride[2] Deposition (mg/m^2)	Model[3] Prediction (mg/m^2)
6B-1	Wax myrtle (control)	1.11	107.8	102.97	-	0
6B-2	Groundsel (control)	1.98	81.5	242.94	-	0
6B-3	Groundsel #1	21.24	74.3	2858.68	2615.74	5000
6B-3	Groundsel #2	20.64	85.8	2405.59	2162.65	5000
6B-4	Wax myrtle #1	1.59	94.3	168.61	65.64	1000
6B-4	Wax myrtle #2	2.48	123.4	200.97	98.00	1000
6B-5	Wax myrtle #1	1.03	100.8	102.18	0	1000
6B-5	Wax myrtle #2	1.32	95.0	138.95	35.98	1000
6B-6	Wax myrtle #1	0.84	98.4	85.37	-	250
6B-6	Wax myrtle #2	0.47	61.7	76.18	-	250

[1]See Figure 14 and text for site locations.
[2]Deposition calculated as amount per unit area minus control for that species.
[3]Predicted deposition based on isopleth map from Rocket Exhaust Effluent Diffusion Model (REEDM).

Table 9. Far-field aluminum deposition from STS-61-B determined from leaf samples.

Site[1]	Species	Amount of Aluminum in Washings (mg)	Leaf Area (cm^2)	Amount of Aluminum per Unit Area (mg/m^2)	Aluminum[2] Deposition (mg/m^2)
6B-1	Wax myrtle	0.03	107.8	2.78	-
6B-2	Groundsel (control)	0.00	81.5	0.0	-
6B-3	Groundsel #1	0.42	74.3	56.53	56.53
6B-3	Groundsel #2	0.45	85.8	52.48	52.48
6B-4	Wax myrtle #1	0.12	94.3	12.73	9.95
6B-4	Wax myrtle #2	0.15	123.4	12.16	9.38
6B-5	Wax myrtle #1	0.09	100.8	8.93	6.15
6B-5	Wax myrtle #2	0.12	95.0	12.63	9.85
6B-6	Wax myrtle #1	0.03	98.4	3.05	0.27
6B-6	Wax myrtle #2	0.00	61.7	0.0	-

[1]See Figure 14 and text for site locations.
[2]Deposition calculated as amount per unit area minus control for that species.

Table 10. Far-field chloride deposition from STS-61-B determined from leaf samples.

Site[1]	Replicate	Density of Deposition Spots (spots/m^2)	Spot Diameter Mean (mm)	Calculated[2] Chloride Deposition (mg/m^2)	Model[3] Prediction (mg/m^2)
6B-4	1	42000	0.945	160.4	
	2	39000	1.080	172.3	
	3	57000	0.990	229.0	
	Mean	46000	-	187.2	1000
6B-5	1	7600	1.09	33.8	
	2	6000	1.01	24.6	
	3	6800	0.94	25.8	
	Mean	6800	-	28.1	1000

[1]See Figure 14 and text for site locations.
[2]Calculated using methods of Anderson and Keller (1983). See text for details.
[3]Predicted deposition based on isopleth map from Rocket Exhaust Effluent Diffusion Model (REEDM).

Table 11. Comparison of aluminum to chloride ratios

Sample[1]	Chloride Deposition (mg/m^2)	Aluminum Deposition (mg/m^2)	Ratio of Aluminum to Chloride (%)
D-1 #1	67.40	0.64	0.95
D-2 #1	43.79	2.43	5.55
D-2 #2	25.66	2.64	10.29
D-4 #1	1622.29	83.32	5.14
D-4 #2	2215.50	107.67	4.86
B-1 #1	4245.96	43.93	1.03
B-1 #2	5303.25	47.05	0.89
B-2 #1	-	3.37	-
B-2 #2	-	3.20	-
B-3 #1	922.64	27.50	2.98
B-3 #2	703.46	39.72	5.65
6B-3 #1	2615.74	56.53	2.16
6B-3 #2	2162.65	52.48	2.43
6B-4 #1	65.64	9.95	15.16
6B-4 #2	98.00	9.38	9.57
6B-5 #1	-	6.15	-
6B-5 #2	35.98	9.85	27.38
6B-6 #1	-	0.27	-
6B-6 #2	-	-	-

[1]See appropriate figures and text for site locations.

decreases with distance from the launch sites while drop number increases, there appears no simple relationship between drop count alone and quantity of deposition.

Measurements of both drop density and drop size are needed in order to estimate quantity of chloride deposition. Such measurements were made for the STS-51-F launch and it was possible to estimate chlorides for two points. One of these was in close agreement with model predictions while the other was substantially less than predicted.

Drop counts and measurements provide a simple and fairly straightforward means of estimating launch deposition. However, drop counts are dependent on the cloud moving over areas with suitable structures for making counts and on assumptions about the concentration of HCl in the droplets. Also, if successive launches impact the same area, distinguishing new from old deposition becomes difficult.

Collection and washing of leaves of plants receiving deposition also provides a simple, direct means of determining far-field deposition. For the three launches analyzed, deposition near the pad (within about 1000 m) but outside the plume zone was similar to the amounts predicted by the REEDM program. Near the predicted centerline, deposition was generally greater than toward the edges of the cloud track. Farther from the pad, observed deposition values were often less than predicted by the model. Ratios of aluminum to chlorides in deposition generally ranged from about 1% to 10%. This is the same range of values found in samples of near-field deposition (Dreschel et al. 1985). This finding suggests that near-field and far-field deposition are qualitatively the same and that leaf washing is an effective means of recovering far-field deposition without obvious bias.

It is, however, important to employ proper controls when using leaf washing to estimate deposition. Leaf canopies accumulate particulate contaminants. Trace metals, including aluminum, accumulate on leaves (Smith 1981); particulate loads can vary seasonally as well as in relation to proximity to point sources and may differ between species. Chlorides accumulate on leaf surfaces in coastal areas due to salt spray (Smith 1981) and are also constituents of leaf tissue (Epstein 1972). Controls should be selected that are of the same species, similar distances inland from the coast so that salt spray deposition is similar, and similar distances from roads or other sources of particulates. The groundsel control sample (B-4) was closer to the coast than the groundsel launch sample (B-2) (Figure 12) and had a greater chloride load (Table 6) even though it had not received launch deposition. Aluminum was, however, in elevated levels in sample B-2 (Table 7). If aluminum deposition is in general about 3% to 10% of chloride deposition from launch, Site B-2 should have had about 30 mg/m^2 to 100 mg/m^2 of chloride deposition which was missed because of the control sample used.

Leaf washing can also only be used where the leaves remain relatively intact so that leaf area can be determined. Where tissue destruction is severe, leaves shrivel on drying so samples must be collected before this occurs. Rain after a launch would limit use of this technique since chlorides are very soluble.

Drop counts and leaf washing gave comparable results for the one launch for which both were done. The wax myrtle control used for

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15. Abstract

Far-field deposition outside of the near-field plume zone occurs from Space Shuttle launches as a result of movement of the launch cloud with prevailing meterological conditions. Paths taken by the launch cloud are highly variable due to varying wind direction and speed. Direction and amount of deposition are predicted by the Rocket Exhaust Diffusion Model (REEDM). Five launches have been sampled to quantify far-field deposition. Drop counts were made for STS-51-A (8 November 1984) but were not sufficient to quantify deposition. Drop counts together with drop size measurements were made for STS-51-F (29 July 1985) and estimates of deposition derived. For two launches, STS-51-D (12 April 1985) and STS-51-B (29 April 1985) leaf samples in the deposition path were collected and washed to recover deposition. Both leaf samples and drop counts were made for STS-61-B (26 November 1985). Measurements of chloride deposition by these techniques ranged from 26 mg/m^2 to 5300 mg/m^2. Aluminum deposition from leaf samples ranged between 0.3 and 107.7 mg/m^2 and was generally between 1% and 10% of chloride deposition. The expected aluminum to chloride ratio in the ground cloud is 86.7%. Reasons for this difference are not known. Estimates of deposition from drop counts and from leaf samples were similar. Measured chloride deposition within the plume zone exceeded REEDM program predictions. Outside the plume zone but within about 1 km of the launch pad, measured deposition generally agreed with model predictions. Farther from the pad, deposition was equal or less than

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15. Abstract

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predicted. Degree of vegetation damage was related to amount of chloride deposition. Serious vegetation damage to many species occurred where chloride deposition values were greater than 1000 mg/m^2; sensitive species were damaged at levels of chloride deposition of 100 mg/m^2 or less.

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